REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
		Final

4. TITLE AND SUBTITLE

Internal State Variable Models for Rate and Temperature History Dependent Behavior at Finite Strain

5. FUNDING NUMBERS

DAAH04-95-1-0177

6. AUTHOR(S)

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7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(ES)

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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

ARO 33559.18-EG

11. SUPPLEMENTARY NOTES

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12a. DISTRIBUTION / AVAILABILITY STATEMENT

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12 b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Under nonisothermal histories typical of metals under impact or deformation processing, dependence on the *history* of temperature and strain rate is potentially first order in terms of material response (McDowell & Voorhees, DSSG Report, IDA, 1995). The principal goal of this program has been to progress towards the next generation of ISV constitutive relations for thermoviscoplastic finite strain behavior of metals. The goals of this research program, which expired at the end of September 1998, were to explore:

- more physically-based representation of the anisotropy of hardening and flow associated with development of dislocation substructure, including kinematical (deformation) as well as kinetics (flow) aspects;
- rate dependence of material strain hardening behavior for strain rates ranging from quasi-static to dynamic, with emphasis on temperature and strain rate *history* dependence, rather than just instantaneous temperature and strain rate dependence.

14. SUBJECT TERMS			15. NUMBER IF PAGES
			16. PRICE CODE
17. SECURITY CLASSIFICATION OR REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT

FINAL PROGRESS REPORT

ARO Grant DAAH04-95-1-0177

INTERNAL STATE VARIABLE MODELS FOR RATE AND TEMPERATURE HISTORY DEPENDENT BEHAVIOR AT FINITE STRAIN

PI/PD: David L. McDowell, Georgia Tech
ARO Monitor: Dr. Kailasam Iyer

STATEMENT OF THE PROBLEM STUDIED

Under nonisothermal histories typical of metals under impact or deformation processing, dependence on the *history* of temperature and strain rate is potentially first order in terms of material response (McDowell & Voorhees, DSSG Report, IDA, 1995). The principal goal of this program has been to progress towards the next generation of ISV constitutive relations for thermoviscoplastic finite strain behavior of metals. The goals of this research program, which expired at the end of September 1998, were to explore:

- more physically-based representation of the anisotropy of hardening and flow associated with development of dislocation substructure, including kinematical (deformation) as well as kinetics (flow) aspects;
- rate dependence of material strain hardening behavior for strain rates ranging from quasi-static to dynamic, with emphasis on temperature and strain rate *history* dependence, rather than just instantaneous temperature and strain rate dependence.

SUMMARY OF THE MOST IMPORTANT RESULTS

The program has produced a set of novel, complex sequence experiments, along with related constitutive model development and numerical implementation/simulation. One of the most complete sets of finite strain baseline, temperature, strain rate and sequence data ever generated in the open literature has been developed in this project for OFHC Cu. Interactions have been maintained with Sandia National Laboratories-Livermore (SNL-L) to collaborate in conducting the experimental component of the program and in the study of grain subdivision phenomena. We have also established strong interactions with Scott Schoenfeld at ARL to evaluate performance of advanced ISV models in applications and to further develop polycrystal plasticity theory and implement into armor/anti-armor analyses. Bob McGinty's work is in close collaboration with ARL.

Significant accomplishments achieved during this grant include:

- completion of a very comprehensive set of finite strain experiments on OFHC Cu over a range of temperatures from room temperature to 0.7 homologous, strain rates from 10^{-4} to 10^{4} s^{-1}, and strains exceeding unity, including deformation, temperature and rate sequences, hold times with relaxation and recovery, etc.; time-temperature measurements were obtained throughout sequences
- characterization and modeling of grain subdivision processes and formation of microtextures within grains, leading to multiple scales of relaxed constraints (effective non-crystallographic slip behavior at grain level) and a novel scaling law ISV evolution law for diffusion of texture
- the introduction of non-Schmid effects in hardening and flow, including coupled hardening of the ISVs for different slip systems and latent hardening descriptions which interact with noncrystallographic features (geometrically necessary dislocation boundaries)
- texture and grain size measurements for various deformation paths, and comparison to standard Taylor polycrystal plasticity theory

- incorporation of emerging tools for determination of ISV constitutive law parameters such as a hybrid gradient, downhill simplex and genetic algorithms for parameter estimation, along with early work in parameter form estimation for ISV laws; establishing this technology as a viable, useful tool for parameter estimation for complex ISV relations, including technology transfer to SNL-L and ARL.
- application of these principles to parameter estimation for the MTS model, the Bammann-Johnson-Chiesa SNL-L model and the modified McDowell ISV model, including effects of dynamic and static recrystallization for OFHC Cu over a wide range of temperatures and strain rates
- implementation of 2-D and 3-D polycrystal plasticity models and corresponding studies of deformation path sequences and design of experiments methodology for assessing essential elements of the structure of polycrystal plasticity models, along with framing of a sliding mesoscale approach which makes use of certain aspects of the orientation distribution of crystallites along with macroscopic flow potentials and hardening laws.

LIST OF PUBLICATIONS AND TECHNICAL REPORTS

1. Horstemeyer, M.F. and McDowell, D.L., "Stress State and History Effects in Viscoplasticity at Finite Strain," in Finite Deformation Viscoplasticity, eds. R.C. Batra and T.W. Wright, ASME MD-Vol. 69-1, 1995, pp. 519-543.
2. Marin, E.B., McDowell, D.L. and Bertoncelli, C., "Models for Compressible Elasto-Plasticity Based on Internal State Variables," International Journal of Damage Mechanics, Vol. 7, No. 1, 1998, pp. 47-83.
3. Miller, M.P. and McDowell, D.L., "Biaxial Deformation Experiments Over Multiple Strain Regimes," in Multiaxial Fatigue and Deformation Testing Techniques, ASTM STP 1280, Kalluri and Bonacuse, Eds., ASTM, 1997, pp. 65-91.
4. Marin, E.B. and McDowell, D.L., "A Semi-Implicit Integration Scheme for Rate-Dependent and Rate-Independent Plasticity," Computers and Structures, Vol 63, No. 3, 1997, pp. 579-600.
5. Lacy, T., McDowell, D.L. and Talreja, R., "Effects of Damage Distribution on Evolution," Applications of Continuum Damage Mechanics to Fatigue and Fracture, ASTM STP 1315, D.L. McDowell, ed., ASTM, Philadelpha, 1997, pp. 131-149.
6. Horstemeyer, M.F. and McDowell, D.L., "Modeling Effects of Dislocation Substructure in Polycrystal Elastoviscoplasticity," Mechanics of Materials, Vol. 27, 1998, pp. 145-163.
7. Butler, G.C. and McDowell, D.L., "Polycrystal Constraint and Grain Subdivision," to appear in Int. J. Plasticity, 1998.
8. Butler, G.C., Graham, S., McDowell, D.L., Stock, S.R. and Ferney, V.C., "Application of the Taylor Polycrystal Plasticity Model to Complex Deformation Experiments," ASME J. Engng. Mater. Techn., Vol. 120, 1998, pp. 197-205.
9. Butler, G.C. and McDowell, D.L., "Polycrystal Constraint and Grain Subdivision," Int. J. Plasticity, September 1998.
10. Graham, S., Lustig, S.K., McDowell, D.L. and Hughes, D.A., "Deformation Induced Anisotropy in Polycrystalline FCC Metals," Proc. Plasticity '97: 6th Int. Symp. on Plasticity and its Current

Applications, Physics and Mechanics of Finite Plastic and Viscoplastic Deformation, Ed. A.S. Khan, Juneau, Alaska, 14-18 July, 1997, pp. 29-30.
11. Tanner, A.B., McGinty, R. and McDowell, D.L., "Deformation, Temperature and Strain Rate History Effects Based on Sequence Experiments," Proc. Plasticity '97: 6th Int. Symp. on Plasticity and its Current Applications, Physics and Mechanics of Finite Plastic and Viscoplastic Deformation, Ed. A.S. Khan, Juneau, Alaska, 14-18 July, 1997, pp. 93-94.
12. McDowell, D.L., "Multiple Scales and Averaging Concepts for ISV Theories," Proc. Plasticity '97: 6th Int. Symp. on Plasticity and its Current Applications, Physics and Mechanics of Finite Plastic and Viscoplastic Deformation, Ed. A.S. Khan, Juneau, Alaska, 14-18 July, 1997, pp. 67-68.
13. Butler, G.C., Guvenilir, A, McDowell, D.L. and Stock, S.R., "Quantification of Grain Subdivision Accompanying Large Deformations of Copper," Proc. Spring MRS meeting, Symp. On Application of Synchrotron Radiation Techniques to Materials Science, San Francisco, April 1998.
14. Tanner, A.B. and McDowell, D.L., "Deformation, Temperature and Strain Rate Sequence Experiments on OFHC Copper," to appear in Int. J. Plasticity, 1998.
15. Tanner, A.B., McGinty, R.D. and McDowell, D.L., "Modeling Temperature and Strain Rate Sequence Effects on OFHC Copper," to appear in Int. J. Plasticity, July 1998.
16. Guvenilir, A., Butler, G.C., Haase, J.D., McDowell, D.L. and Stock, S.R., "X-ray Microbeam Quantification of Grain Subdivision Accompanying Large Deformations of Copper," submitted to Acta Materialia, February 1998.
17. Lacy, T.E., McDowell, D.L. and Talreja, R., "Nonlocal Concepts for Evolution of Damage," submitted to Mechanics of Materials, July 1998.
18. McGinty, R.D. and McDowell, D.L., "Multiscale Polycrystal Plasticity," submitted to special issue of ASME J. Engng. Mater. Techn., July 1998, presented at SES Fall Meeting, Pullman, WA, September 1998.
19. McGinty, R.D. and McDowell, D.L., "Variable Resolution Mesoscale Polycrystal Plasticity," Proc. ICES '98, Modeling and Simulation Based Engineering, Atlanta, Georgia, October 6-9, 1998, pp.1438-1443.
20. Butler, G.C., Guvenilir, A, McDowell, D.L. and Stock, S.R., "Quantification of Grain Subdivision Accompanying Large Deformations of Copper," Mat. Res. Soc. Symp. Proc. Vol. 524, April 1998, pp. 43-48.

In Preparation:

1. Horstemeyer, M.F., McGinty, R.M. and McDowell, D.L., "Polycrystalline Elastoviscoplasticity: A Parametric Study," submitted to J. Modelling & Simulation, November 1998.

2. McGinty, R.D. and McDowell, D.L., "Variable Resolution Polycrystal Plasticity," to be presented at Plasticitity '99, Cancun, Mexico, January 1999.

Presentations

1. McDowell, D.L., "Modeling Multiscale Phenomena with Internal State Variables," invited seminar, Dept. of Mechanical Engng., Clemson University, Clemson, SC, January 24, 1997.
2. Graham, S., Lustig, S.K., McDowell, D.L. and Hughes, D.A., "Deformation Induced Anisotropy in Polycrystalline FCC Metals," Proc. Plasticity '97: 6th Int. Symp. on Plasticity and its Current Applications, Physics and Mechanics of Finite Plastic and Viscoplastic Deformation, Ed. A.S. Khan, Juneau, Alaska, 14-18 July, 1997.
3. Tanner, A.B., McGinty, R. and McDowell, D.L., "Deformation, Temperature and Strain Rate History Effects Based on Sequence Experiments," Proc. Plasticity '97: 6th Int. Symp. on Plasticity and its Current Applications, Physics and Mechanics of Finite Plastic and Viscoplastic Deformation, Ed. A.S. Khan, Juneau, Alaska, 14-18 July, 1997.
4. McDowell, D.L., "Multiple Scales and Averaging Concepts for ISV Theories," Proc. Plasticity '97: 6th Int. Symp. on Plasticity and its Current Applications, Physics and Mechanics of Finite Plastic and Viscoplastic Deformation, Ed. A.S. Khan, Juneau, Alaska, 14-18 July, 1997.
5. McDowell, D.L., "Deformation, Rate and Temperature History Effects: Implications for ISV Models," Sandia National Laboratories, Livermore, CA, July 30, 1997.
6. McDowell, D.L., "Evolving Structure and Internal State Variables," Nadai Lecture, moderator S. Nemat-Nasser, ASME IMECE, Dallas, TX, November 20, 1997.
7. Tanner, A.B., McDowell, D.L. and McGinty, R.D., "Study of Macro- and Meso-Scale ISV Models for Complex Histories,"13th U.S. National Congress of Applied Mechanics, University of Florida, June 21-26, 1998.
8. Butler, G.C., Morano, R., McDowell, D.L. and Stock, S.R., "Polychromatic Synchrotron X-ray Diffraction Quantification of Grain Subdivision Accompanying Large Deformations of Copper," presented at 47th Annual Denver X-ray Conference, 3-7 August, 1998, Colorado Springs, CO.
9. McDowell, D.L., "Constitutive Equations and Length Scales in Solids," University of Michigan, Midwest Mechanics Lecture Series, Invited Lecture, February 16, 1998.
10. McDowell, D.L., "Polycrystal Plasticity and Subgrain Heterogeneity," Michigan State University, Midwest Mechanics Lecture Series, Invited Lecture, February 17, 1998.
11. McDowell, D.L., "Constitutive Equations and Length Scales in Solids," Northwestern University, Midwest Mechanics Lecture Series, Invited Lecture, February 18, 1998.
12. McDowell, D.L., "Polycrystal Plasticity and Subgrain Heterogeneity," University of Wisconsin-Madison, Midwest Mechanics Lecture Series, Invited Lecture, February 19, 1998.
13. McDowell, D.L., "Constitutive Equations and Length Scales in Solids," University of Minnesota, Midwest Mechanics Lecture Series, Invited Lecture, February 20, 1998.
14. McDowell, D.L., "Constitutive Equations and Length Scales in Solids," Johns Hopkins University, Dept. of Mechanical Engineering, Invited Lecture, April 2, 1998.
15. "ISV Relations for Solids," Sandia National Laboratories, Livermore, CA, July 7, 1998.
16. McDowell, D.L., "Applications in Crystal Plasticity," Conference in Mechanics of Material, invited participant, Mathematisches Forschungsinstitut Oberwolfach, Oberwolfach, Germany, Aug. 23-29, 1998.
17. McDowell, D.L., "Some Comments on Averaging Approaches for Multiscale Internal State Variable Constitutive Equations," Technische Universität München, Germany, September 1,

1998.
18. McGinty, R.D. and McDowell, D.L., "Multiscale Polycrystal Plasticity," submitted to special issue of ASME J. Engng. Mater. Techn., July 1998, presented at SES Fall Meeting, Pullman, WA, September 1998.
19. McGinty, R.D. and McDowell, D.L., "Variable Resolution Mesoscale Polycrystal Plasticity," Proc. ICES '98, Modeling and Simulation Based Engineering, Atlanta, Georgia, October 6-9, 1998, pp. 1438-1443.
20. McDowell, D.L., "Use of Nonproportional and Sequence Experiments to Study the Structure of ISV Constitutive Relations," 35th Annual Technical Meeting, Society of Engineering Science, Washington State University, Pullman, WA, Sept. 27-30, 1998.

Three papers related to this research were presented by D.L. McDowell at the Sixth International Symposium on Plasticity and Its Current Applications held in Juneau, Alaska July 14-18, 1997. A paper summarizing the work by Buck Tanner was given at the 13th U.S. National Congress of Applied Mechanics held at the University of Florida in June 1998. A paper on the sliding mesoscale model under development within the AASERT program was presented at the SES meeting at Washington State University held September 27-30, 1998. Numerous invited lectures have also arisen from this work.

Theses and manuscripts have been forwarded during the course of the research to ARO for reporting purposes.

PARTICIPATING SCIENTIFIC PERSONNEL

Dr. D.L. McDowell, Regents' Professor of Mechanical Engineering and Materials Science and Engineering and Director of the Mechanical Properties Research Laboratory at Georgia Tech, served as the Principal Investigator/Project Director. He led the modeling effort and coordinated all aspects of modeling and experimentation, technology transfer, etc.

LTC Albert "Buck" Tanner began pursuit of his doctorate in September 1995. Buck's efforts were primarily dedicated towards the experimental investigation of rate and temperature sequences of OFHC Cu. He was principally concerned with the study of rate and temperature history effects in both mesoscale and macroscale constitutive models, and developed some principles for assessing the dominance of competing mechanisms and associated forms for dynamic and static thermal recovery terms. This work has led to tools that can facilitate employment of sophisticated internal state variable constitutive models by analysts relatively unfamiliar with the details of these models. Buck graduated in Spring 1998. He is presently at ARL.

Mr. Robert McGinty has been in the PhD program since summer 1995. He is focusing on the implementation of 3-D polycrystal viscoplasticity, and is conducting deformation, temperature and strain rate simulations with the intent of developing improved slip system level internal state variable models. His doctoral work is focusing on the development of a "sliding mesoscale" hybrid internal state variable (ISV) model that combines elements of the kinematics of polycrystal plasticity with a macroscale level treatment. Bob spent several weeks with Scott Schoenfeld at ARL working on

application of his 3-D elasto-plastic polycrystal implementation in ABAQUS and a material point simulator. He spent much of September 1998 and will spend part of summer 1999 at ARL in Aberdeen.

Mr. George (Chip) Butler is a Ph.D. student who was supported by an AASERT Award from 1994-97. Chip has performed an extensive characterization of texture evolution in deformation path sequence experiments for OFHC Cu at room temperature, and has recently performed Laue measurements of microtexture within individual grains on the Stanford linear accelerator. He has developed an unique micromechanical-based ISV modification of the structure of crystal plasticity to include grain subdivision by geometrically necessary boundaries and the resulting microtextures, utilizing scaling laws for refinement of subgrains and local misorientation developed at Sandia Livermore by Darcy Hughes and colleagues. He is presently developing ISV hardening laws that incorporate geometrically necessary dislocations in 2-D and 3-D polycrystal plasticity models. The final phase of his work involves implementation in a 3-D code and associated simulations/verification. Mr. Butler is anticipated to finish his degree in Winter 1999.

Theses Generated

1. Horstemeyer, M.F., "Physically Based Models for Deformation-Induced Anisotropy," PhD Thesis, August 1995. Dr. Horstemeyer is presently at Sandia National Laboratories in Livermore, CA.

2. Tanner, A.B., "Modeling Temperature and Strain Rate History Effects in OFHC Cu," PhD Thesis, June 1998. Dr. Tanner is presently at ARL in Aberdeen, MD.

HONORS & AWARDS OF SUPPORTED PERSONNEL

Honors include:

D.L. McDowell

1. NADAI Award, ASME Materials Division, 1997
2. Institute Fellow, Georgia Tech, 1994-1999
3. Regents' Professor, Georgia Tech, 1996-present
4. Editorial Advisory Board, International Journal of Plasticity, 1991-present.
5. Technical Editor, ASME Journal of Engineering Materials and Technology, 1997-present.
6. Editorial Advisory Board, International Journal of Damage Mechanics, 1993-present.
7. Editorial Advisory Board, International Journal of Fatigue and Fracture of Engineering Materials and Structures, 1994-present.
8. Regional Editor, International Journal of Fracture, 1997-present.
9. Named Carter N. Paden, Jr. Distinguished Chair in Metals Processing at Georgia Tech in September 1998.
10. Named to the Alumni Board of the Dept. of Mechanical and Industrial Engineering at the University of Illinois at Urbana-Champaign, Sept. 1998.

In 1997, Dr. McDowell participated in two DoD planning efforts:

- Member, Panel on Modeling and Simulation, Naval Studies Board study on Technology for Future Naval Forces, National Research Council, Washington, D.C., 1995-1997. Co-authored "Technology for the United States Navy and Marine Corps, 2000-2035: Becoming a 21st Century Force: Volume 9 - Modeling and Simulation," National Academy Press, 1997.

- Member, Defense Science Board Task Force on Underground Facilities, 1997-present.

TECHNOLOGY TRANSFER

This program has involved ongoing interactions with Sandia National Laboratories, Livermore, CA (SNL-L).
Participants at SNL-L, by area of technical interest, include:

D.J. Bammann - Macroscale modeling
D. Mosher & W. Kawahara - Experimental techniques for high strain rate deformation and sequence experiments
M. Horstemeyer - Micro- to macro- models; coordination of Sandia with GT effort
D. Hughes - microstructure evolution; grain subdivision/refinement processes

This work is relevant to the core mission of Sandia, which relies on increasingly accurate models for prediction of rate and temperature-dependent material behavior at large strain, both in defense and civilian manufacturing applications. In fact, SNL-L has found Buck Tanner's methodology for parameter estimation as embedded in the commercial software package **Pointer** extremely useful in ongoing programs. In fact, they report that it has fostered tremendous progress in some of their large research and development programs which rely on application of internal state variable models. It is highly likely that this will translate to the Army as well through Buck Tanner's present association with ARL.

An important feature of this program is interaction with U.S. Army research personnel at APG in Aberdeen. Scott Schoenfeld visited Georgia Tech in early 1997 and Bob McGinty spent several weeks in summer 1997 and September 1998 at ARL with Dr. Schoenfeld. It is envisioned that this collaboration will continue and will lead to significant results and advances, as well as a close connection of our research programs to analysis activities at ARL.